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Final Technical Report

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Office of Naval Research

for contract *number*

N00014-81-k-0457.

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Final Technical Report

This report is the Final Technical Report in for Office of Naval Research contract N00014-81-K-0457, which ended September 30, 1985. This contract was to the the University of California, Davis with James S. McClain as the Principle Investigator.

History

This contract commenced in 1981, shortly after my arrival at the University of California at Davis. The initial work proposed was to analyze Project ROSE data, and to invert it for the three dimensional structure of the oceanic crust under the East Pacific Rise. The results of this project were somewhat disappointing, because the ROSE archive system at the Hawaii Institute of Geophysics suffered a major failure and were not able to deliver data to Davis until late in the project. However, we developed a substantial amount of software for the handling of seismic data and the benefits of the contract continue now.

In 1983 we changed the emphasis of the contracted science. Pointing out that the long-term evolution of the oceanic crust was not well understood, we proposed to gather data for a seismic transect of the Pacific Ocean spanning ages of 0 to 60 million years. The data we used was from a series of seismic refraction profiles that were conducted in the 1950 s. Although the data was high quality, much of it had hardly been touched, and none of it had ever been digitized for use on a computer. In our project we digitized data from 7 profiles and have analyzed these profiles using modern techniques.

In 1985 the formal contract ended, although research has continued at a lower level. Our results show that any long-term evolution of the crust in the Pacific is small compared to the normal variability of the structure created when the it is formed at the mid-ocean ridges. Of particular importance, we showed that thickening of the oceanic crust was a relatively minor, which contradicts a number of earlier studies that indicated substantial thickening of the crust as it aged.

At present, although not under formal contract with the Navy, we are continuing to analyze the data that we acquired during the contract. We have two major emphases: First we are analyzing the data for transition zones in the upper crust, and second we are examining the structure of the oceanic uppermost mantle using data from ROSE, from our older data, and from the MAGMA project (a NSF funded experiment). In addition, I am a participant in the SNAG group and a consortium formed to expand the capabilities of the Ocean Bottom Seismometer.

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The Long-Term Evolution of the Oceanic Crust.

The Rationale for the Project.

The most important characteristic about the seismic structure of the oceanic crust is its striking uniformity (e.g. Shor et al, 1970; Christensen and Salisbury, 1975). However, a number of studies have indicated that the oceanic crust thickens by large amounts as it ages away from the mid-ocean ridges (e.g. Goslin et al, 1972; Christensen and Salisbury, 1975; Lewis and Snydsman, 1977; McClain and Lewis, 1980).

The mechanism cited for this thickening is the progressively deeper serpentinization of the oceanic upper mantle as the lithosphere gets older. Serpentinization results from the hydration of peridotite at relatively low (< 450° C) temperatures. Seismic velocities of the peridotites are lowered to crustal values, and hence the hydrated mantle is added at the base of the crust, and the crust appears to thicken. The moho becomes a hydration boundary rather than a petrological one. This model contradicts the prevailing view that the lower crust is composed of gabbro. Furthermore the above-cited studies indicate as much as 30% of the oceanic crust is "created" away from the mid-ocean ridges. Thus, the thickening of the oceanic crust, if it exists, is one of the fundamental processes acting at the surface of the earth.

We argue that the long-term thickening of the oceanic crust, and the evolution of the crust in general, should be examined. We proposed to study this phenomenon using two approaches. First, we did a statistical study of a large number of seismic refraction results to see if thickening was statistically significant. Second, we proposed to examine a number of profiles forming a transect across the South Pacific and spanning ages from 0 to 60 Ma.

Procedures for the Project.

Statistical Study

For the statistical portion of our study, we collected all of the seismic refraction results that we could find for the Pacific Ocean. We attempted to eliminate all profiles over unusual structures such a seamounts, fracture zones or plateaus. Rather than examine the thicknesses of the different crustal layers we used the total crustal thickness as a function of age.

In our study we divided the crust into 10 million year age intervals, and into the two intervals of 0 to 30 Ma. and >30 Ma. In both cases we computed the mean thicknesses of the crust, and then did formal statistical tests comparing the means. These tests included the "testing the difference of the means", the "Mann-Whitney test", and the " median test" (e.g. Daniel, 1978).

In addition to the examination of the variations in the mean crustal thicknesses, we also made a linear regression of crustal thickness as a function of age for profiles over crust with ages of 0 to 10 Ma.

Profile-by-profile Study

We selected a number of profiles from two cruises that extended across the Southern Pacific Ocean (Figure 1). They formed a transect that spanned ages from 0 to 90 Ma. These data were collected in 1952-53 and 1957, and were originally analyzed using least-squares fits to travel times. In general, these studies did not make use of second arrivals, and they never used waveform or amplitude information. The profiles were selected because of their position and because a brief examination of the data showed them to be high quality, with relatively smooth bathymetry and low signal to noise ratio.
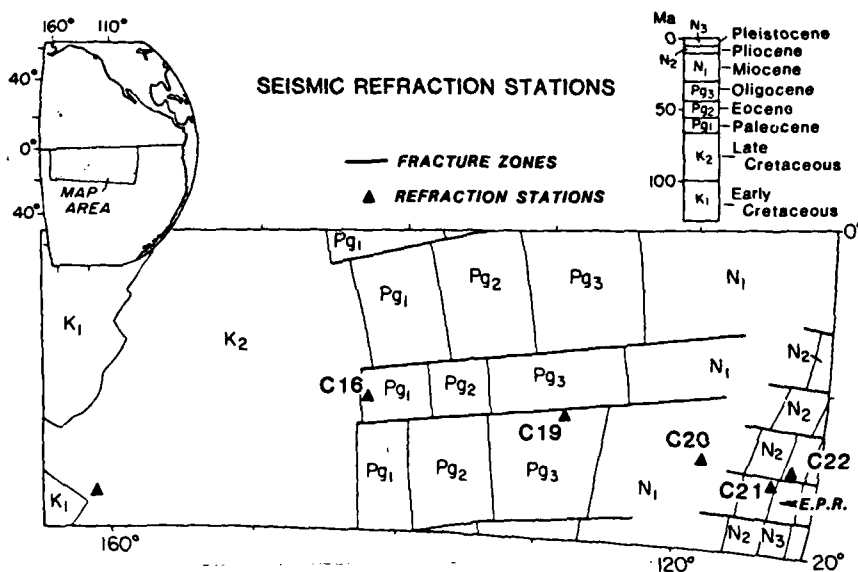

Figure 1. Chart of South Pacific, showing locations of seismic refraction stations used in this study and ages of sea floor. E.P.R. = East Pacific Rise.

The initial work on this project entailed the digitization of the seismograms. The original records, on photosensitive paper, are kept in the data archives at the Scripps Institution of Oceanography. They are made available by George Shor and Russell Raitt at S.I.O. The analog records were digitized using a HP pad, then the data was converted to ROSE format. Header information, including source and receiver parameters, were then merged with the seismograms. All of these seismograms are from hydrophones suspended from a receiving ship, with a shooting ship firing shots as it steamed into and away from the former.

The ROSE formated files are available for plotting using standard techniques (e.g. Figures 2 and 3). Plotting record sections enabled us to identify arrivals including shear waves and second compressional arrivals that could not be identified from single analog seismograms alone. Each profile used in this study had a split-leg configuration. We chose the leg that appeared to be the best behaved (i.e. the least complications due to lateral heterogeneity or uneven seafloor). Bathymetric corrections were made to the data by the technique of Purdy (1982; see also Spudich and Orcutt, 1980; McClain et al, 1985).
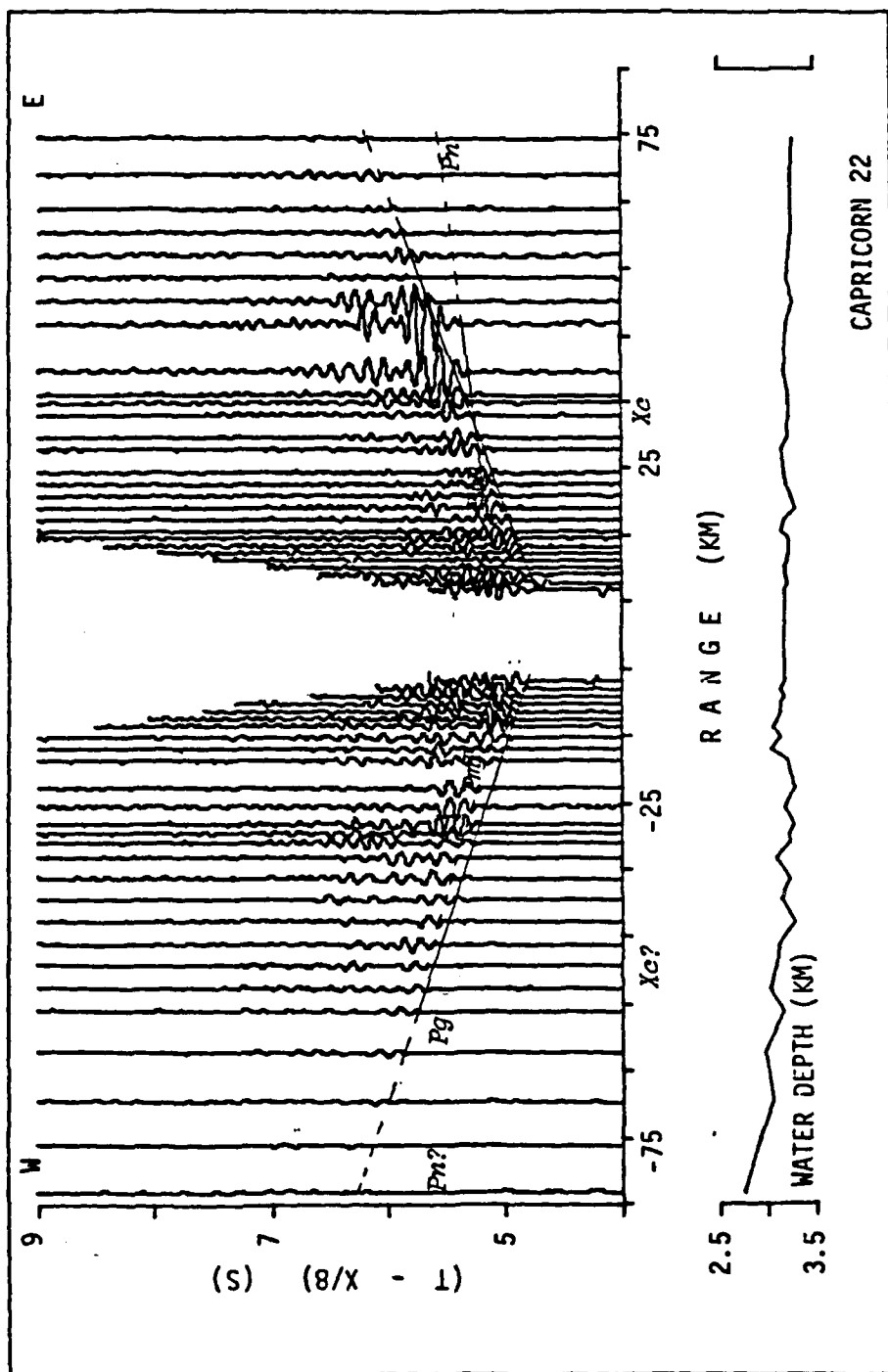
Figure 2. Record section of seismograms from Capricorn 22, over very young crust (1 Ma). Although the seismograms are very clean (low noise), they display no converted shear waves.
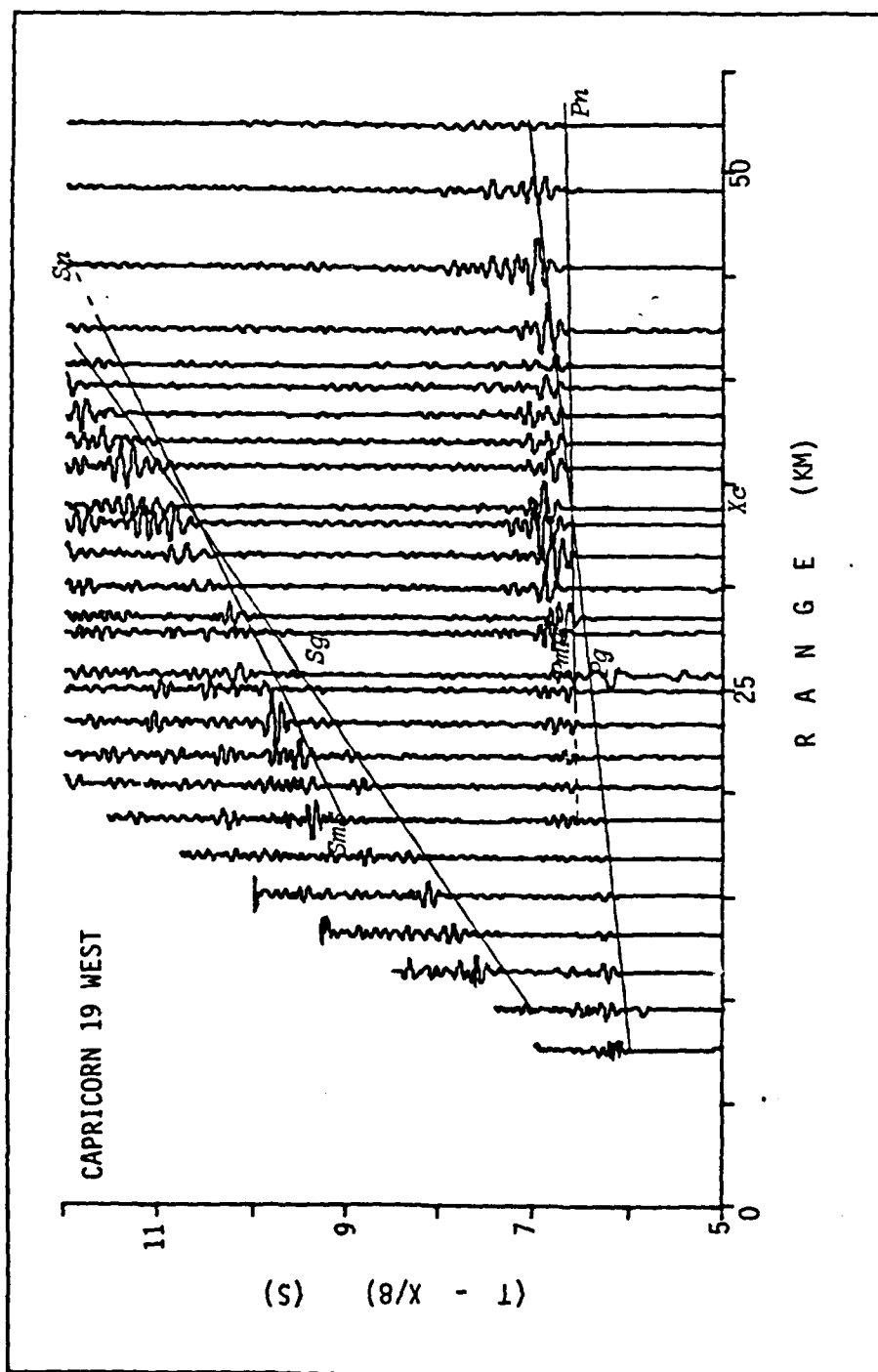
Figure 3. Seismograms from Capricorn 19, over 29 Ma. crust. Note the excellent shear waves on this profile, compared to their absence on Capricorn 22 over young crust. This is do to a change in the properties of the seafloor as the crust ages.

To model the data we first attempted to match arrival times using a simple ray-tracing approach. We entered velocity-depth pairs, and used a computer program that makes use of Filon's Method, where the travel-time and distance integrals are evaluated by assuming a simple function between each pair (in our case, our program assumes a linear velocity depth function). The resulting solvable integrals are summed to make the complete integral over depth. As a result of using a number of models for a given profile, we were able to find a "best" model. This in turn was used as a starting model for more careful modeling using a WKBJ program for modeling the travel times, amplitudes and waveforms of the seismic arrivals. A large number of models were tested using the synthetic seismograms, and the best model for each profile was determined.

Results of the Study

Statistical Study

In our preliminary paper (McClain, 1981) we showed that grouping the crustal thickness into 10 Ma. intervals indicated that there was no statistically significant difference in the the thicknesses of the crust between the intervals. However, when grouped into ages 0 - 30 Ma. and >30 Ma., we found the older crust to be slightly thicker. While this apparent thickening was very slight compared to earlier studies (.45 km compared to as much as 1.5 km in earlier work), it was significant.

Our early research revealed a fundamental error in the early analysis of the seismic refraction data. Crustal thicknesses for each profile were the sum of the layer 2 and layer 3 thicknesses. Layer 1, thought to be sediments, were not included in my analysis. However, in many seismic refraction profiles over younger parts of the seafloor, the layer 1 velocities were not directly observed. The presence of a layer 1 was inferred from the non-zero intercept time of the layer 2 arrivals (after the water had been removed). The assumption that this "hidden" layer was sediments allowed computation of the sediment thickness. Because many of these analyses were done before seafloor spreading was discovered, early workers were not aware that profiles over young crust should have little or no sediments at all. For example, profiles near the East Pacific Rise typically resulted in models with several hundred meters of sediments. In fact, such thicknesses were impossible, and the hidden layers were undoubtedly basalts, and should be included in the total crustal thicknesses. This was done, and the resulting crustal thicknesses for young crust were substantially increased.

We concluded in 1981, that the apparent crustal thickening was an artifact of the above errors. In our 1985 paper we added new data for the statistical analysis and expanded the analysis to use more rigorous tests of changes in thickness. We found a smaller change in crustal thickness (0.34 km) that was still statistically significant under all tests. (see Figure 4)
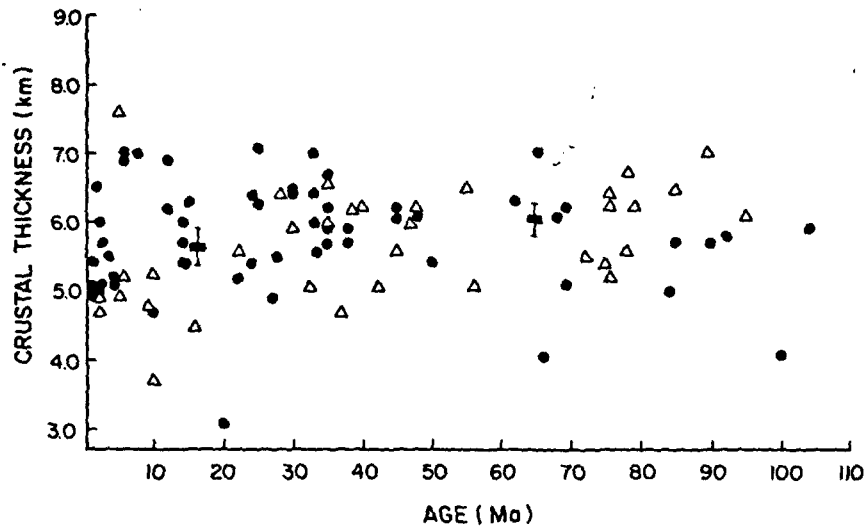
Figure 4. Plot of crustal thicknesses vs. age for 100 different seismic refraction results. Horizontal bars show averages between 0 and 30 Ma and between 30 and 100 Ma. Error bars denote standard deviations of estimated means. Solid circles represent most reliable data; triangles represent less reliable data.

We also attempted a linear regression on crustal thicknesses as a function of age for all profiles over crust with ages 0 to 10 Ma. We found that the slope of the curve was -0.007 $^+$ .06 km/Ma. That is, no resolvable thickening of the crust in the first 10 million years.

Our major conclusion from the statistical study is that while statistically significant thickening occurs, it is not an important process. Because mechanisms for thickening exist (ongoing volcanism and serpentinization), while there are no known mechanisms for crustal erosion or thinning the statistical thickening of the crust must occur. However, while the average thickness of the crust is expected to increase, our results suggest that the average crust does not thicken.

Profile-by-profile profile study

In our profile-by-profile study we chose the best five of our profiles from crust with ages of 1., 2., 14., 29., and 60 million years. In the original, layered analysis of these profiles (done in 1952-53) it was found that the thickness of the crust increased monotonically with age (see Figure 5) In our reanalysis we found that the original models were woefully inadequate in duplicating the seismic amplitudes and waveforms. After numerous attempts, we were able to produce new models that better matched the data.

Figure 2. Plots of
compressional-wave ve-
locity vs. depth (excluding
water and sediments) for
five profiles analyzed.
Top: Crustal structure de-
termined from original
layer solutions to travel-
times; dashed line con-
nects depths of Moho
beneath sea floor. Bottom:
Results obtained using
synthetic seismogram and
ray-trace modeling. Be-
cause of gradational na-
ture of crust-mantle
boundary, crustal thick-
ness is defined as depth
of velocity 7.6 km/s.

VELOCITY (km/s)

DEPTH (km)

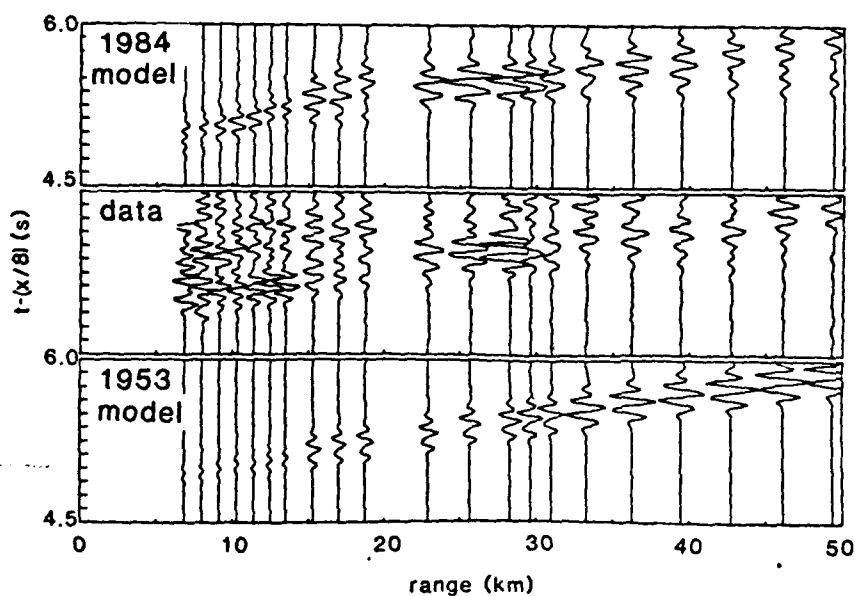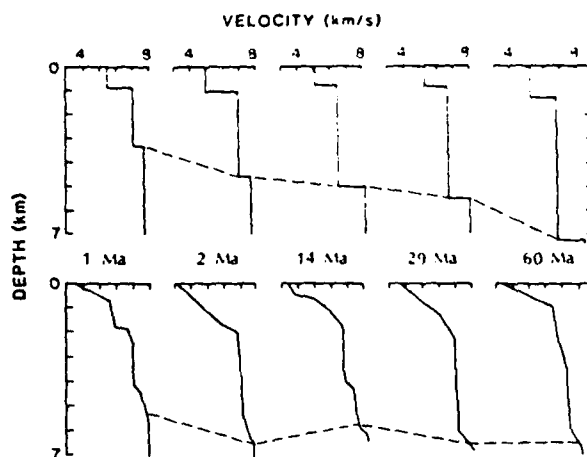1 Ma   2 Ma   14 Ma   29 Ma   60 Ma

t-(x/8) (s)

range (km)

Figure 3. Example of record section of seismograms after digitizing original analog data (cen-
ter). Seismograms have been plotted at appropriate source receiver distance. They have been
shifted in time to correct for bathymetric variations beneath sources, and amplitudes have been
changed to correct for source size and distance. Above and below data are corresponding
synthetic seismograms generated from our best model (1984 model, above) and from layered
solution originally derived from traveltimes alone (1953 model, below). Although both models
reproduce traveltimes fairly well, amplitudes and waveforms of upper synthetics resemble data
more closely. Note that real seismograms are more complex than synthetics, a result of crustal
reverberations and scattering off lateral heterogeneities. These effects are not included in
computation of synthetics shown here.

From these models were found the following:

1. The systematic increase in crustal thickness observed on the original structures does not exist. Instead, crustal thicknesses appear to vary randomly. Combining these results with those of the statistical test we argue that for the most part thickening of the oceanic crust with age is **not an important or fundamental process in the oceanic crust.**

2. A number of the profiles exhibit a mid-crustal transition zone (see Figure 4). This transition zone has been reported by other workers (e.g. Spudich and Orcutt, Bratt and Purdy, Lewis and Garmany), but we were the first to point out that it appears to be a widespread feature in the ocean crust. We suggest that it is the boundary or fossil boundary between the relatively permeable uppermost crust and the impermeable lower crust. This boundary would thus be the lower limit to pervasive water penetration and alteration of the crust. This means that the cooling of the lower oceanic crust, and in particular the magma chambers of the mid-ocean ridges, may occur by the restricted and perhaps episodic penetration of water, rather than pervasive penetration.

   This mid-crustal transition zone is most prominent on younger profiles, implying, but not proving, that the zone may evolve with age. Such evolution is reasonable, for we might expect that the abrupt change in porosity would be smeared out by the precipitation of alteration products in the pore spaces. Similar mechanisms have been cited as the cause for increasing seismic velocities in the uppermost crust in the Atlantic (Houtz and Ewing, 1976).

3. Shear wave velocities in the oceanic crust are less well resolved but appear to yield roughly the same structures as the P waves. The shear wave moho is at the same position as the P wave moho (see Figure 7). Shear waves only appear upon older profiles. This suggests that alteration of the crust, and the deposition sediments raises the velocity contrast at the basement to allow for the efficient conversion of shear waves at the basement interface. Young, unsedimented seafloor has too low a velocity to produce converted shear waves. This result is consistent with the results of Lewis and McClain (1977))

4. One of the profiles we used, Capricorn 22, actually crossed the East Pacific Rise at 15°S. It was thus the **only profile ever conducted over an ultrafast spreading center.** Thus we had a unique opportunity to test for the presence of a huge magma chamber, as is expected from numerical models for the cooling crust. We found no evidence for such a huge structure. This shows that hydrothermal cooling makes magma chambers small even under the fastest spreading ridges (McClain and Atallah, 1985).
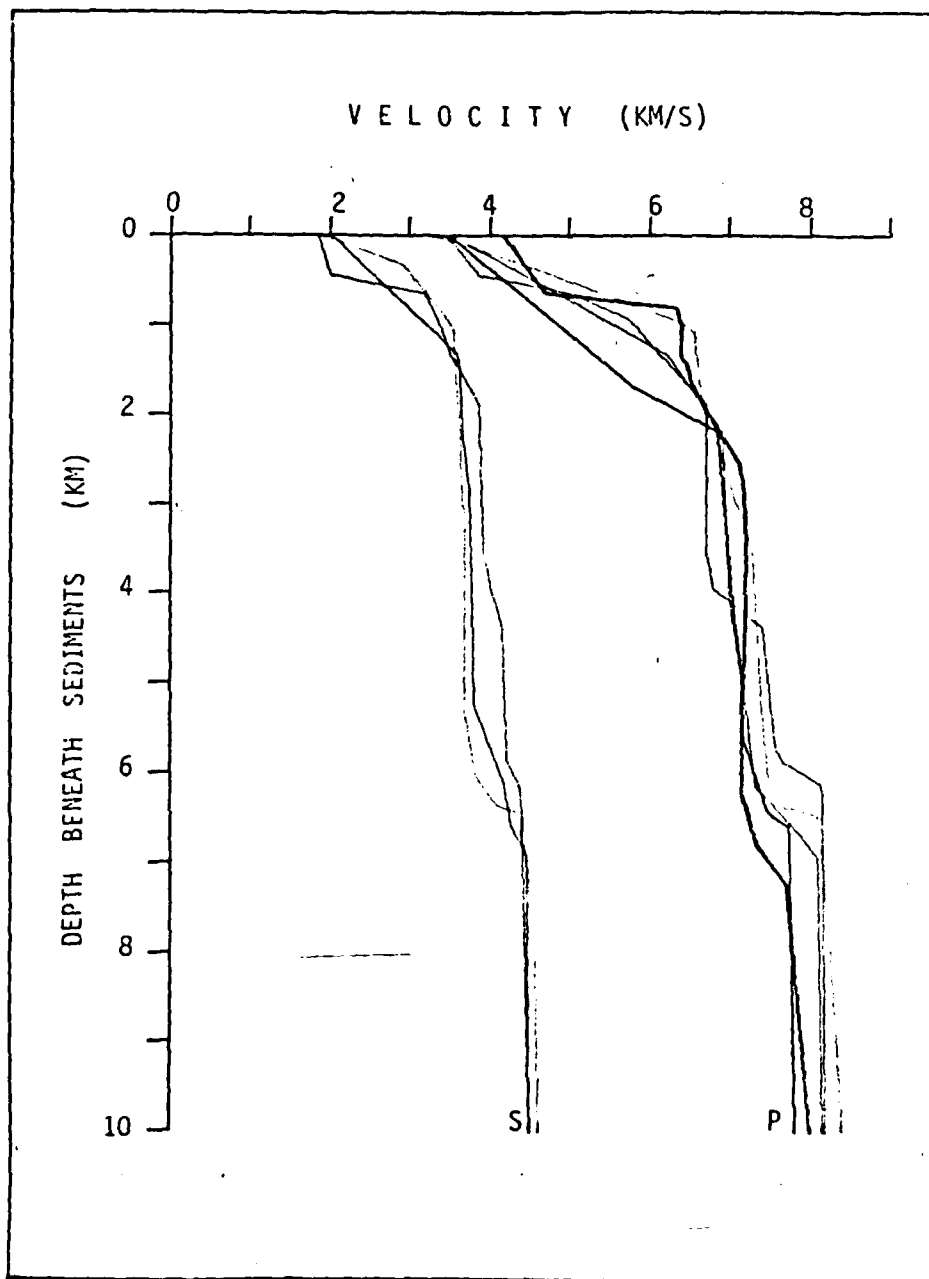
Figure 7. Collection of velocity-depth structures found
found in this study. Our results show that the
shear and compressional wave structures mimic
each other.

Published and Presented Results

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2. Orcutt, J.A., and J.S. McClain, Seismic constraints on the origin and evolution of the oceanic crust and uppermost mantle, Chapman Conference on the Generation of the Oceanic Lithosphere, 1981.

3. Atallah, C. and J.S. McClain, Evolution of P and S velocities in the oceanic crust and upper mantle, *EOS, Trans. Am. Geophys. Un., 64,* 1983.

4. Atallah, C.A., and J.S. McClain, Is long term thickening of the oceanic crust really occurring? *EOS, Trans. Am. Geophys. Un., 65,* 1012, 1985.

5. McClain, J.S., and C. A. Atallah, The structure of young oceanic crust near a very fast spreading ridge, *Geophys. Res. Lett., 12,* 689-692, 1985. **Copy enclosed.**

6. McClain, J.S., and C.A. Atallah, The structure of young oceanic crust near a fast spreading ridge, *EOS, Trans. Am. Geophys. Un., 66,* 1985.

7. McClain, J.S., E.M. Moores, and Chen Chin, Seismic velocities and the penetration of water into the crust at mid-ocean ridges, *EOS, Trans. Am. Geophys. Un., 67,* 1244, 1986.

8. McClain, J.S., and C.A. Atallah, The thickening of the oceanic crust with age, *Geology, 14,* 574-576, 1986. **Copy enclosed.**

9. Atallah, C.A., and J.S. McClain, The evolution of oceanic seismic structure, in preparation, 1987.

ON LONG-TERM THICKENING OF THE OCEANIC CRUST

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Abstract. A number of studies of seismic refraction data have resulted in suggestions that the oceanic crust thickens with age, perhaps over a long time span. It is difficult to reconcile notions of crustal thickening with many of our ideas about crustal structure and formation. In this study we have re-evaluated data compiled from a number of sources to obtain crustal thickness and age parameters for 105 different refraction profiles in the Pacific. An attempt was made to exclude data which might have poorly determined values of crustal thickness. The crust does appear to thicken with age to 30 or 40 m.y., but the effect is very subtle. Once probable biases are removed from the data, crustal thickening is not significant to a 95% confidence limit if ten m.y. samples are used. However, if one takes sample intervals of 0-30 m.y. and 30-100 m.y. there appears to be some difference in the average crustal thickness. Even in the latter case, the amount of thickening is far less than previous studies have suggested, only .45 km. Thus evidence for the long-term addition of mass to the crust remains tenuous.

Introduction

In the last decade researchers have demonstrated an apparent correspondence between ophiolite complexes observed on land and oceanic crustal structure determined by seismic refraction studies (Christensen and Salisbury, 1975). The upper oceanic basement (classically referred to as "Layer 2" in seismic refraction results) is equivalent to extrusive pillow basalts and the lower crust (layer 3) would correspond to intrusive sheeted dikes and cumulate gabbros seen in ophiolites. The crust-mantle boundary, or seismic moho, is believed to correspond to the transition between the gabbros and olivine cumulates.

This ophiolite structure is set by the sea floor spreading process, and while hydrothermal alteration continues to modify the petrology of the crust, the fundamental structure is believed to remain constant with time. Specifically, the ophiolite model does not explicitly allow for the addition (or removal) of mass from the oceanic crust as it ages. However, crustal thickening has been reported from seismic refraction results; the first such report being by Le Pichon et al. (1965). Shor et al. (1971) suggested that layer 3 (the lower oceanic crust) may thicken with age. Goslin et al. (1972) made a statistical study of the same data and concluded that layer 3 does indeed undergo significant thickening to an age of 40 million years. They further conclude that this

apparent thickening requires the addition of mass the crust and suggest that serpentinization of the upper mantle, which may lower the mantle velocities to crustal values, is the responsible mechanism. The seismic moho would thus correspond to the hydration boundary in the ultramafic rocks rather than the gabbro-olivine boundary as inferred from ophiolites. Christensen and Salisbury (1975) also conclude that layer 3, and hence the crust, thickens with age to 30 million years. Desiring to preserve the ophiolite model (albeit modified), they suggest that ongoing igneous intrusion is the cause. Woollard (1975) proposed that thickening occurs out to 50 m.y. Given the importance of these seismic observations it is the intent of this paper to re-examine the statistical evidence for the long term addition of mass to the oceanic crust. This paper will exclude the discussion of evidence for short term thickening (within the first few million years) which has also been reported (e.g. Lewis, 1978).

Procedure

In this work we have taken Pacific basin crustal structures from the data compilation of Shor et al. (1971) and added additional data from Fisher and Raitt (1962), Hussong et al. (1975), Meeder et al. (1977), Lewis and Snydsman (1979); Spudich and Orcutt (1978), and McClain and Lewis (1980). Age data are taken from Heezen and Fornari (1976), Sclater et al. (1980), and D. Sandwell (personal communication). In this study, we utilize total crustal thickness; that is the depth to moho minus the water depth and sediment thickness. Since the layering of the crust merely represents velocity ranges, the thickening of any one layer may represent a change in velocity rather than the addition of new mass.

The data from all sources were examined for possible structural complications which would put their interpretations in doubt and make their application to this problem suspect. Sources for these checks include Raitt (1956) and D. McGowan (personal communication) as well as the previously mentioned papers. Seismic results were eliminated from the study if the refraction lines were definitely over fracture zones, seamounts, or the volcanics of the Hawaiin Chain. Also eliminated were lines showing evidence of great lateral heterogeneity. No claim is made that this cursory inspection eliminated all of the problem data and different refraction lines were subjected to varying levels of evaluation depending on the available information. However, an attempt was made to maintain objectivity.

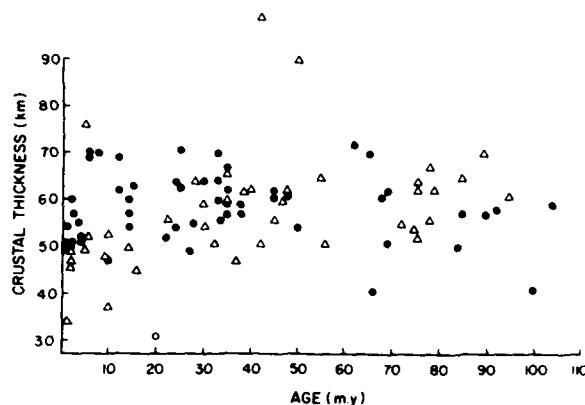Data from north of the Mendocino Fracture

Figure 1. Plot of crustal thickness versus age for Pacific Ocean. Dots represent the most reliable data. See text.

Zone, where sea floor spreading rates are much slower, was eliminated from this study. Refraction and gravity results from near the Gorda Rise yield extremely thin young crust (Dehlinger et al., 1970). It is possible that this region is anomalously thin due to factors also responsible for the large rift valley and anomalous upper mantle observed to occur. If these processes (here unspecified) have changed with time then the crust may vary in thickness, but any given segment will not gain mass. By eliminating these northern refraction results we risk introducing a bias into the study. However, if the addition of material to the crust is a general feature of the Pacific basins, then evidence should be preserved in the remaining majority of the data.

The 105 remaining data points used in this project are shown in Figure 1, which is a plot of total crustal thickness versus age. A qualitative evaluation of the points is shown with triangles denoting the less reliable data. Reasons for down-grading (but not eliminating) a refraction profile included unusual crustal or upper mantle velocities, uncertainty in crustal ages, or possible structural complications.

In order to examine the statistics of long term crustal thickening we have divided the data into 10 million year increments and calculated the sample means (m), standard errors (s) and the estimated standard error of the means (S   S/(n)$^{\frac{1}{2}}$). The results are detailed in Table I. Also shown are these values for the intervals 0-30 m.y. and 30-100 m.y. Both Table I and Figure 2 show an increase in crustal thickness with age. In fact the crust appears to continue thickening out to the 30 - 40 m.y. interval. Thickness variations beyond that age are not systematic.

The next step is to determine if the difference between means of two given age groups is significant. For this we estimate the difference in population means (simply the difference between sample means, $m_1 - m_2$) and the pooled standard error Sp,

$$\text{(1)}$$

$$\text{where } Sp \quad \{ \sum_{1}^{n_1}({}_1 y_i - m_1)^2 + \sum_{1}^{n_2}({}_2 y_i - m_2)^2 \} \frac{1}{n_2 + n_2 - 2},$$

with n_1 referring to the number of points in the first sample and n_2 being the number of points in the second sample. We then compute the t statistic for the difference between our estimated difference in means and a hypothetical difference D_0.

$$\text{Therefore, } t \quad \frac{(m_1 - m_2) - D_0}{S_p (\frac{1}{n_2} + \frac{1}{n_2})^{\frac{1}{2}}} . \qquad \text{(2)}$$

We wish test the hypothesis that the true difference in population means is zero (D_0 0), and use a one-tailed t test (we only care if the change in thicknesses is greater than zero). Shown in Table II are the t values for various age group pairs. Also given is whether the hypothesis should be rejected or accepted to a confidence level of 95% (considered statistically significant). The hypothesis is rejected for the interval pairs (0-10), (30-40) and (10-20), (30-40) which means that the data support a difference in the oceanic crustal thicknesses between those intervals. The hypothesis is accepted for the interval pair (20-30), (30-40) which indicates that increase in crustal thickness with age beyond 20 m.y. is not statistically significant from analysis of these data. Thus, evidence for crustal thickening is preserved at least for the first 20 million years. Other interval pairs are not included here because the number of points is small, the variance is large or the difference in means is very low.

Possible Biases

In the data of Shor et al. (1971) substantial effort was made to provide a standardized analysis of the available Pacific refraction data. This was important for comparison of results and represented a significant contribution to marine geophysics. However, later workers must be cautious when re-using the data.

One layer, that of sediments, was many times not observed on the seismic refraction

Table I. Average Thicknesses For Different Crustal Ages.

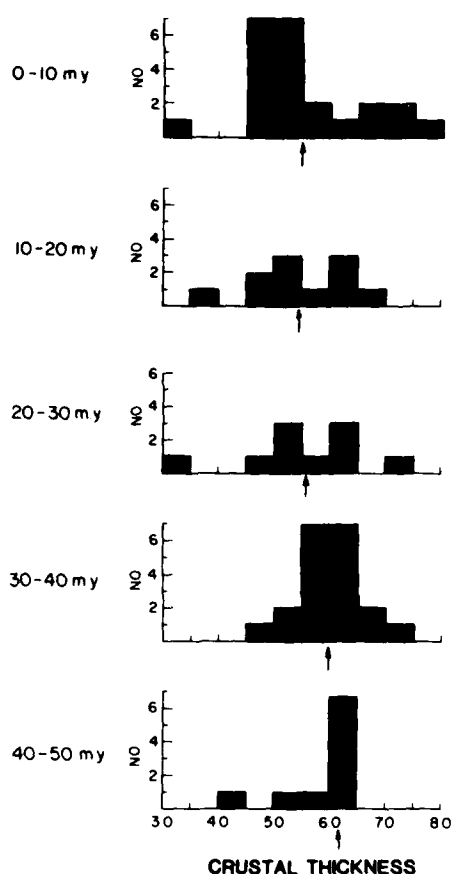| Age (m.y.)	No.	Mean	S	Sm
(0-10)	22	5.49	1.01	.22
(10-20)	11	5.43	.92	.28
(20-30)	10	5.58	1.11	.35
(30-40)	20	5.96	.53	.12
(40-50)	11	6.17	1.38	.42
(50-60)	4	6.50	1.77	.89
(60-70)	6	5.95	1.17	.48
(70-80)	8	5.90	.54	.19
(80-90)	4	6.04	.87	.44
(90-100)	3	5.87	.21	.12
>100	6	6.23	1.37	.56
(0-10)'	22	5.59	.94	.20
(0-10)"	22	5.65	.92	.20
(0-30)"	43	5.58	.94	.14
(30-100)	56	6.03	.92	.12

CRUSTAL THICKNESS

Figure 2. Histograms of crustal thicknesses for ten million age spans. Arrows denote means.

profiles. Instead it was assumed, because the intercept time from the underlying basement was not zero (after the water layer was removed). In the older regions of the oceans this is a reasonable expectation. However, in younger regions sediment thicknesses are thinner and we may expect the observed basement to be overlain by still more igneous basement, with low velocity due to very high porosity. This low velocity igneous layer has been directly observed by Houtz and Ewing (1976) and Houtz (1976). Labeled by them layer 2A, this region usually has a velocity of between 3 and 4 kilometers per second and appears to become thinner with increasing age. This thinning is probably because cracks in the rock are mineralized and velocity increases to normal crustal values (Schreiber and Fox, 1976).

We examined data from 0-6 million year old crust for refraction profiles located in the southern mid-latitudes, where sedimentation rates are very low (e.g. Heezen and Fornari, 1976). While little or no sediment would be expected, we found assumed sediment thicknesses on five lines of 300 to 500 meters. These undoubtedly actually represent layer 2A thicknesses, and thus are a part of the igneous crust and should be included in the total crust thicknesses rather than subtracted. Doing this changed the average crustal thickness for the

0-10 million year old crust ((0-10)' on Table I); enough to allow us to change our conclusions concerning the significance of crustal thickening (Table II). That is, we can no longer reject the hypothesis that the crustal thicknesses are the same for those two time intervals.

In the preceeding argument we used the same P wave velocity as the 2.15 km/sec assumed for the hypothetical sediments. In fact, layer 2A velocities are probably higher and we have assumed a new velocity of 3.5 km/sec and recomputed the layer solutions. The thickness of this hidden layer will be greater since the same delay time must be taken up by this higher velocity. As expected the average crustal thickness for these modified data are greater (labeled (0-10)" in Tables I and II), and the long term crustal thickening as evidenced by comparing the (0-10)" and (30-40) m.y. crusts is even less convincing.

However, even with these corrections, there appears to be a significant difference between young (0-30)" and very old (30-100) ocean crust. The change in average crustal thickness is quite small, only .45 kilometers.

It must be emphasized that these corrections would probably be applicable to other refraction lines in the (0-10) and (10-20) m.y. intervals, but since these lines also may have some sediment this was not done. With the published data it was not possible to separate the contributions of sediment and igneous to the hidden layer. Hence, the corrections obtained here must represent a minimum.

Discussion

While significant differences in crustal thickness remain when viewed through a large averaging window, the process of thickening cannot be broken down into smaller age increments. The evidence for thickening from this study are far less convincing that the earlier studies of Goslin et al. (1972), Christensen and Salisbury (1975), and Woollard (1975) and given the earlier discussed biases, the long-term addition of mass to the crust (excluding sediments) remains in doubt.

If crustal thickening does not occur, how are the observations of dramatic layer 3 thickening explained? The answer may lie in a general increase in seismic velocities with age. Houtz and Ewing (1976) and Houtz (1976)

Table II. Statistics of Thickness Variations

Age Pair	δm	Sp	t Value	Hypothesis Reliability
(0-10)(10-20)	-.07	.98	.19	Accept
(0-10)(30-40)	.47	.82	1.88	Reject
(10-20)(30-40)	.53	.69	2.04	Reject
(20-30)(30-40)	.38	.77	1.27	Accept
(0-10)(40-50)	.68	1.14	1.62	Accept
(0-10)'(30-40)	.37	.77	1.54	Accept
(0-10)"(30-40)	.31	.76	1.35	Accept
(0-30)"(30-100)	.45	.93	2.38	Reject

suggested the such increases in velocity may explain the apparent disappearance of layer 2A with increasing age. As the velocity increases this uppermost layer becomes part of the underlying "layer 2B". Thus, we may expect layer 2 (exclusive of 2A) to appear to thicken with age. However, analysis suggests that layer 2 thickness remains constant (Goslin et al., 1972) or decreases (Christensen and Salisbury, 1979) in the long term. The excess thickness must be going into layer 3 by the mechanism of slowly increasing velocity in the base of layer 2. This would explain the apparent decrease in layer 3 velocities with age noted by Houtz (1976). Layer 3 velocities are being "contaminated" by the relatively low velocities of layer 2. Thus layer 3 thickens by virtue of redistribution of materials between layers and not by actual addition of material to the crust.

Decoupling the effects of sedimentation and velocity variation from those of crustal thickening remains a difficult problem. However, given the importance of thickening for models of hydrothermal circulation and crustal evolution, these problems must be resolved.

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Thickening of the oceanic crust with age

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ABSTRACT

The most widely accepted models for ocean-crust formation and composition fail to predict the thickening of the oceanic crust with age, yet such thickening has been described in the Pacific Ocean for years. To reconcile this apparent long-standing conflict, we have reexamined the evidence for the thickening of the Pacific crust by using a statistical treatment of a large number of seismic profiles and by doing a detailed reanalysis of several profiles forming a transect across the southern Pacific Ocean. From the statistical studies, we find that crust younger than 30 Ma has a mean thickness of 5.67 km, whereas crust between 30 and 100 Ma has a mean thickness of 6.01 km. This 0.34-km difference, although statistically significant, is far less than that reported in several previous studies. Our results from the South Pacific transect suggest that changes in the crustal thickness are not systematic, and from both studies it appears that crustal thickening is not particularly important. The small thickening that we do observe is probably the result of isolated processes that are not active under the oceanic crust as a whole. As a result, arguments favoring a large component of serpentinite in the crust cannot be based upon evidence for crustal thickening beneath the Pacific Ocean.

INTRODUCTION

The oceanic crust covers some 60% of Earth's surface, and the processes responsible for the generation and evolution of that crust have a fundamental importance for the earth sciences. The oceanic crust, which we define as the crystalline rocks between the sediments and water above and the Moho below, is necessarily studied by indirect means, usually seismic refraction. Seismic experiments have revealed a crust that is strikingly uniform in structure (e.g., Shor et al., 1970), evidence that the major processes acting under the seas are similar throughout the world. Numerous attempts have been made to correlate the seismic results with geologic studies of dredged rocks and of land-bound ophiolites, and in the past 15 years there has been widespread acceptance of the so-called ophiolite model for the oceanic crust. In that model, the uppermost crust consists of pillow basalts that overlie a sheeted-dike unit. The sheeted dikes, in turn, overlie units of massive and cumulate gabbros, which form the lower crust. The base of the crust, or the Moho, is marked by a transition between the gabbros and mantle peridotites (e.g., Moores and Vine, 1971; Christensen and Salisbury, 1975; Spudich et al., 1978; Kempner and Gettrust, 1982).

Explicit or implicit in most such models is the corollary that the oceanic crust is generated in its entirety by igneous processes at the mid-ocean ridges. Although ongoing alteration of the crust must be occurring, the basic structure remains locked in place after formation. Hence, the ophiolite model fails to predict the thickening of the crust with age, and yet such thickening has been described by many workers through the years. Some seismic studies seem to show thickening near the axis of the East Pacific Rise (Lewis and Snydsman, 1977), and several show impressive thickening (1 to 2 km) over periods of as much as 40 m.y. (Le Pichon et al., 1965; Goslin et al., 1972; Christensen and Salisbury, 1975). As several workers have pointed out, such changes require a substantial rethinking about the nature of the oceanic crust and the processes that form it. The most popular mechanism invoked for the thickening of the crust is the progressively deeper penetration of water into the oceanic upper mantle. This would serpentinize the mantle peridotites and lower their seismic velocities to crustal values. The Moho would then be a hydration boundary within the mantle peridotite, and as much as the lower 30% of the crust would be serpentine rather than gabbro (Lewis and Snydsman, 1977; Meeder et al., 1977; Lewis, 1983). Christensen and Salisbury (1975), advocating a modified ophiolite model, suggested that the crust thickens because of ongoing igneous intrusion beneath the sea floor. While this mechanism preserves a gabbroic composition for the lower crust, it requires that this intrusion continue in the lithosphere as it ages to some 30 Ma, an important departure from the idea that the average oceanic crust is entirely emplaced at the mid-ocean ridges.

Before accepting such revisions, we have attempted to characterize long-term ocean-crustal thickening and to reconcile the apparent contradiction between the ophiolite model and the seismic observations. We have taken two approaches: the detailed examination of a few seismic refraction profiles from crusts of different ages, and a statistical study of the crustal thicknesses from many profiles in the Pacific Ocean. In this paper we present our conclusions from these two different approaches.

PROFILE-BY-PROFILE

We selected a group of profiles that formed a transect across the southern Pacific Ocean and spanned ages from 1 to 60 Ma (Fig. 1). These profiles were conducted during the Capricorn Expedition of the Scripps Institution of Ocean-
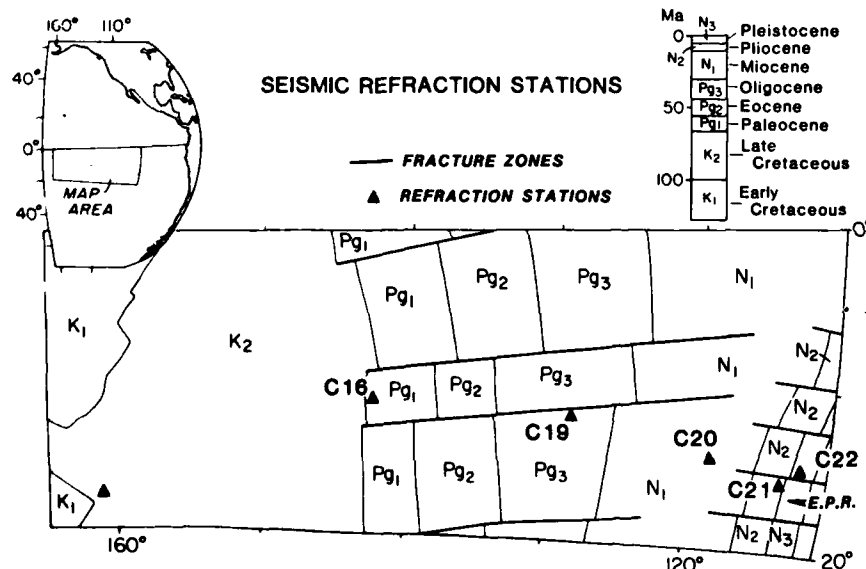

Figure 1. Chart of South Pacific, showing locations of seismic refraction stations used in this study and ages of sea floor. E.P.R. = East Pacific Rise.

...ny, 1952–1953, and were originally analyzed by using the seismic travel times and by assuming a layered ocean-crust structure. The profiles revealed a systematic increase in crustal thickness with age (Fig. 2, upper) (Shor et al., 1970).
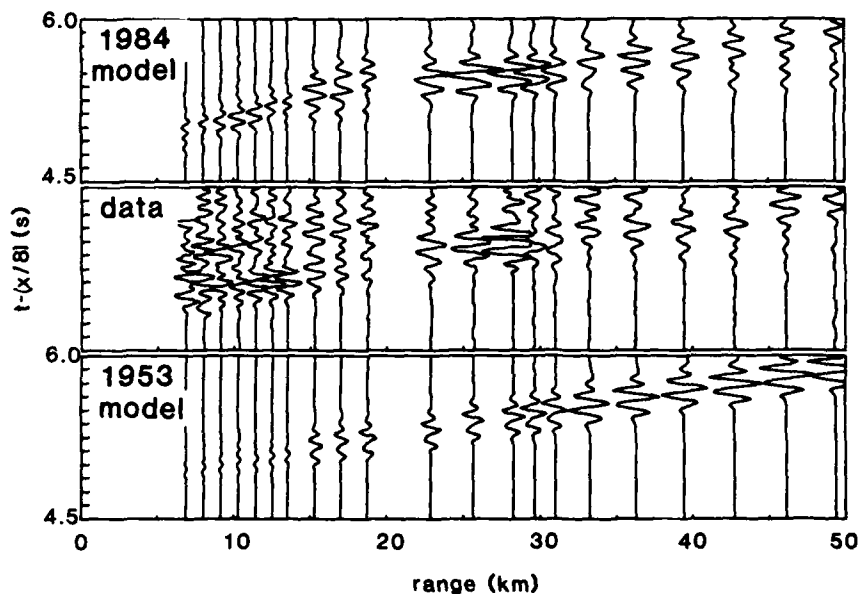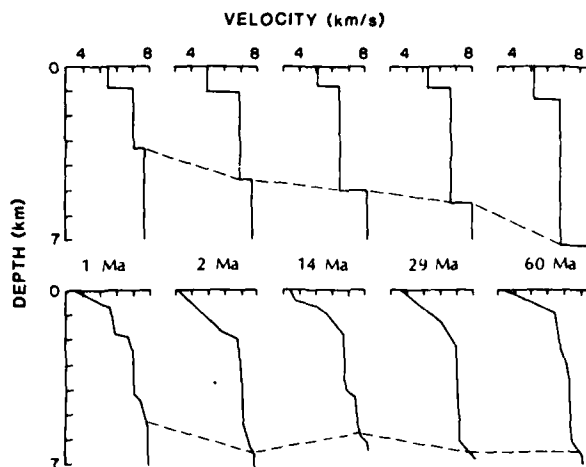
We digitized the seismograms from each profile for use on a computer, which enabled us to make record sections (for an example, see Fig. 3). This, in turn, allowed us to correlate arrivals between seismograms and to examine the waveforms and amplitudes of the seismograms as well as the traveltimes (Fig. 3, center). Each profile consisted of two independent legs, and we chose the one with the best data (the one exhibiting the least influence of lateral heterogeneities) and attempted to duplicate the amplitudes, waveforms, and traveltimes with synthetic seismograms generated numerically from model velocity structures. We used the WKBJ algorithm (Chapman, 1978), which presumes a laterally homogeneous and nonattenuating earth. After trying many models for the structure under each profile, we chose the one that best simulates the data; this model represents the best (we hope) laterally homogeneous approximation to the earth.

We found substantial differences between our results and those originally derived for these data, and the newer structures clearly are superior (Fig. 3). When all of these new structures are plotted together, we find that the systematic increase in crustal thickness originally seen for this transect is not observed under our more careful scrutiny. The exact depth of the Moho is more difficult to define, for it is a transition zone rather than an abrupt boundary. However, by any consistent definition for the base of the crust, the thicknesses are highly irregular, values varying between about 5 and 7 km (Fig. 2, lower). In fact, both the thickest and thinnest crusts occur at the two youngest sites.

STATISTICAL STUDIES

The results of profile-by-profile studies, like the one just described, cannot necessarily be applied to the oceans in general. Instead, statistical studies of large numbers of refraction results must be made; indeed, the most convincing evidence for crustal thickening has come from such studies (Le Pichon et al., 1965; Goslin et al., 1972; Christensen and Salisbury, 1975). These earlier studies were influenced by profiles that were over anomalous regions of the sea floor and were also influenced by the layered approximations to crustal structure (McClain, 1981). We attempted to avoid some of these problems by eliminating profiles that were over seamounts or known fracture zones. We also included a substantial number of structures from more recent experiments (Fig. 4). It is important to note that it is not feasible to reanalyze all the profiles used in this statistical

study; hence, some of the scatter in the data can be attributed to the varying and sometimes outmoded methods of analysis used on the different profiles.

Because we were most interested in the long-term thickening of the crust and in making statistically meaningful comparison between crusts of different ages, we divided the crust into age intervals of 10 m.y. and wider. The most useful division (because it gave us a large number of

profiles in each interval) was to group the crusts into those younger than 30 Ma (44 profiles) and those between 30 and 100 Ma (56 profiles). For the former group of profiles the median crustal thickness was 5.55 km; the mean thickness and standard deviation were 5.67 and 0.88 km, respectively. For the older crusts, the corresponding values were 6.0, 6.01, and 0.91 km, respectively. The difference between the two means is 0.34 km, far smaller

Figure 2. Plots of compressional-wave velocity vs. depth (excluding water and sediments) for five profiles analyzed. Top: Crustal structure determined from original layer solutions to traveltimes; dashed line connects depths of Moho beneath sea floor. Bottom: Results obtained using synthetic seismogram and ray-trace modeling. Because of gradational nature of crust-mantle boundary, crustal thickness is defined as depth of velocity 7.6 km/s.

Figure 3. Example of record section of seismograms after digitizing original analog data (center). Seismograms have been plotted at appropriate source receiver distance. They have been shifted in time to correct for bathymetric variations beneath sources, and amplitudes have been changed to correct for source size and distance. Above and below data are corresponding synthetic seismograms generated from our best model (1984 model, above) and from layered solution originally derived from traveltimes alone (1953 model, below). Although both models reproduce traveltimes fairly well, amplitudes and waveforms of upper synthetics resemble data more closely. Note that real seismograms are more complex than synthetics, a result of crustal reverberations and scattering off lateral heterogeneities. These effects are not included in computation of synthetics shown here.

than the 1 and 2 km of thickening reported in other studies.

We used three statistical tests of the significance of the change in crustal thickness. First, following McClain (1981), we used a t statistic and tested for the significance of the difference of the means. We found that the difference was indeed significant at a 95% confidence level. However, because the data were not normally distributed (a requirement for the rigorous use of the t test), we also relied on the Mann-Whitney test and median test from nonparametric statistics (e.g., Daniel, 1978). Whereas these tests provide less information about the differences between the populations, they also require less of the data. Like the t test, the nonparametric tests indicated a significant difference in the thickness of the crust between the two age groups.

DISCUSSION

In our previous work, we suggested that statistically significant thickening was probably an artifact of erroneous data and that a more complete study would show no thickening (McClain, 1981). On the contrary, our studies reported here show that some change in the average thickness of the crust appears to be real.

The 6% to 8% change in the thickness of the crust from our statistical studies and the variable crust seen from our profile-by-profile study suggest that ocean-crust thickening is far less important than previous workers have indicated. Taking the extreme view, our results mean that a typical section of oceanic crust has a layer, roughly 0.34 km thick, added after

(perhaps long after) it has spread away from the rise axis. We suggest an alternative view. Serpentinization of the upper mantle and ongoing igneous processes may act to locally thicken the oceanic crust, perhaps by large amounts. There are no known corresponding processes that would thin or erode the crust, and so the apparent average thickness must increase with age. The small change that we observe is diagnostic of the fact that these processes are not necessarily widespread and that typical oceanic crust may not thicken at all.

The study described above was sensitive only to long-term thickening of the crust. To test for thickening over a shorter time span, we did a linear regression on crustal thickness as a function of age for profiles over crust 10 m.y. old and younger. We found a slope of -0.007 km/m.y. with a standard deviation of 0.06 km/m.y.; that is, there is no change in observed crustal thickness in the first 10 m.y. This means that the formation of a large component of serpentine in the oceanic crust must occur very close to the spreading center, if ever, and cannot be resolved by these data. It should be noted, however, that the high temperatures expected near the axis make the formation of large amounts of serpentine unlikely.

CONCLUSIONS

It appears that the "ophiolite" model for the oceanic crust is not contradicted by observations of crustal thickening, for our reexamination of the evidence for crustal thickening shows that it is, at most, a relatively minor process acting beneath the Pacific sea floor.

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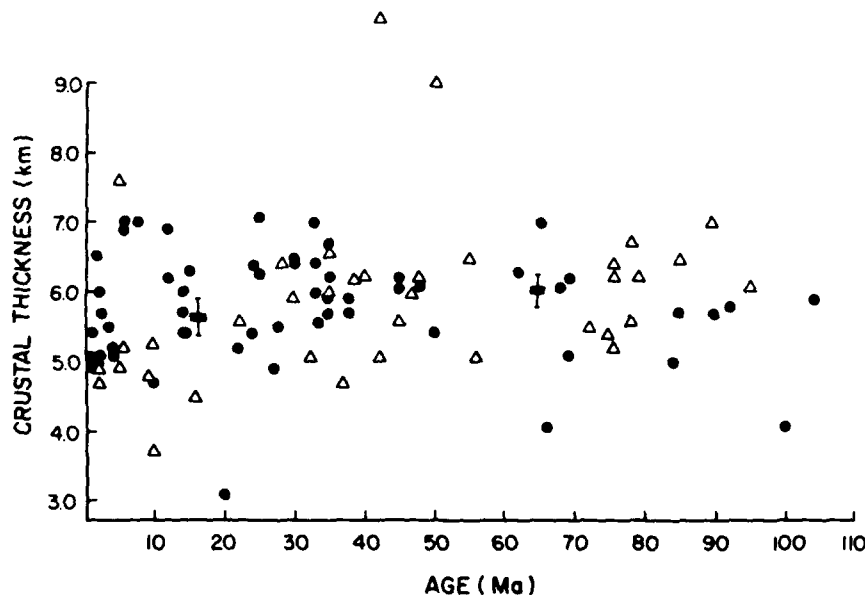
Figure 4. Plot of crustal thicknesses vs. age for 100 different seismic refraction results. Horizontal bars show averages between 0 and 30 Ma and between 30 and 100 Ma. Error bars denote standard deviations of estimated means. Solid circles represent most reliable data; triangles represent less reliable data.

THE STRUCTURE OF YOUNG OCEANIC CRUST NEAR A VERY FAST SPREADING RIDGE

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Abstract. We have modeled the structure of the young oceanic crust near the fastest spreading ridge ever to be profiled using seismic refraction techniques. The data were originally collected during the Capricorn expedition of the Scripps Institute of Oceanography in 1953. One of the split leg profiles from that expedition, C22, was conducted near the East Pacific Rise at 15°S, where the half spreading rate is over 80 mm/yr. By digitizing the data, and modeling the two splits of C22 using synthetic seismograms, we have found that the crust is normal in thickness (5 to 7 km) and in velocity structure. An upper crustal transition zone is present on both legs and would appear to be a regular feature of young oceanic crust. It is probably too deep (1.5 to 2 km beneath the seafloor) to be correlated with the boundary between pillow basalts and sheeted dikes. Instead, we attribute this transition zone to changes in crustal porosity and/or hydrous minerals in the oceanic crust. From the appearance of wide-angle moho reflections near the rise axis, we suggest that the very large crustal magma chamber that might be expected under this fast spreading ridge is not present. This presumably results from the cooling of the crust by pervasive hydrothermal circulation.

Introduction

In the analysis of data from any marine seismic experiment, it is necessary to compare the resulting velocity structure with that of "normal" oceanic crust. That such normal crust can be characterized is not surprising because the processes of crustal formation are widely believed to be similar at the world's mid-ocean ridges. The normal crust is about 6 kilometers thick and the lower crust, "layer 3", usually has velocities of around 6.7 to 7.2 km/s, with a rather low velocity gradient (e.g. Shor et al., 1970; Christensen and Salisbury, 1975). For the upper crust the gradients are high and the velocities highly variable. Recently, a number of papers describing results for experiments over young seafloor have revealed that a transition zone (a region of high velocity gradient) lies between the upper and lower crust (Spudich et al., 1978; Lewis and Garmany, 1982). Bratt and Purdy (1984) have suggested that this transition zone, which they call layer 2C, may mark the boundary between sheeted dikes below and pillow basalts above.

Unfortunately, of the profiles over young seafloor, very few were over crust generated by fast spreading ridges. It is expected that the

thermal structure of a fast spreading center will be much different than that of a slow spreading center. These differences could lead to the presence of an unusually large crustal magma chamber (e.g. Sleep, 1975; Kusznir and Bott, 1976) and might be expected to produce abnormal crust (Menard, 1967). As a part of a larger study, we have selected data from seismic refraction profiles along a transect across the southern Pacific Ocean. One of these profiles actually crossed the East Pacific Rise near 15°S. Using the relative plate motion model (RM2) of Minster and Jordan (1978), we have computed the spreading rate at this lattitude to be about 82 mm/yr; making this the fastest spreading ridge ever to be profiled using seismic refraction. Given the growing interest in fast spreading centers we have given special attention to this profile, with the hope of addressing two important questions. First, is the vertical seismic structure generated by a fast spreading ridge different from the normal crust described above? Second, is there evidence for an unusually large magma chamber under the ridge?

Our profile, labelled Capricorn 22 (C22), was one of many shot during the Capricorn Expedition conducted in 1953 by the Scripps Institute of Oceanography. Like all of the profiles of that expedition it had a split leg configuration, with a shooting ship steaming into and away from a receiving ship at the center (Figure 1). The former fired charges ranging in weight between 1.13 and 36.16 kg while the latter recorded the seismograms detected with suspended hydrophones. In the original experiment, seismograms were recorded in analog format, the travel times picked and a layered solution found. The resulting structure was striking, for it revealed an unusually thin crust of only 3.4 kilometers (Shor et al., 1970)

In our work we have digitized the original records, and plotted the data in record section format (Figure 2). This allowed us to correlate arrivals between shots and examine the data for later arrivals. We divided the two legs of C22 and analysed them independently (the southwest and northwest profiles). In the analysis of these data, we attempted to duplicate the arrival times, relative amplitudes and waveforms of the seismograms using synthetic seismograms generated with the WKBJ algorithm (Chapman, 1978). Any such approach can only provide a "best" vertically stratified model, and the lateral heterogeneities (including bathymetry) of the true earth assure that the agreement between the real data and the synthetics will be limited.

Southwest Profile

The profile extending to the southwest from the receiving ship actually crossed the axis of
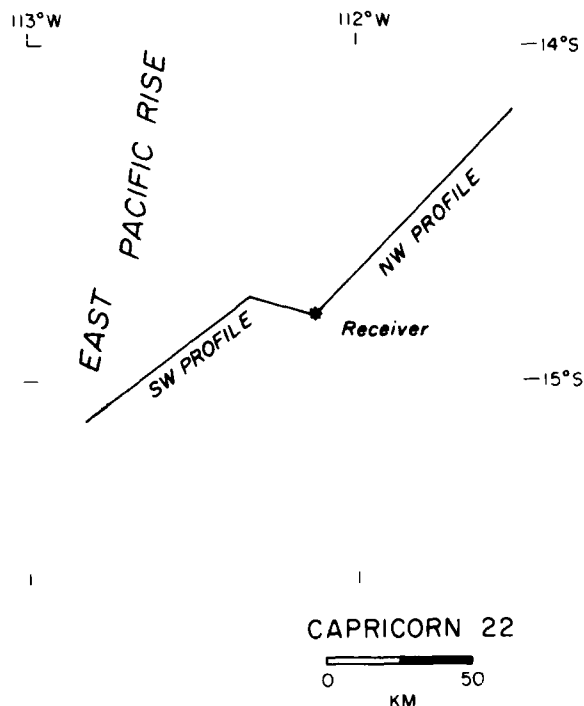
Figure 1. The location of the Capricorn 22 pro-
file relative to the East Pacific Rise. The con-
figuration of the rise is based on the chart of
Mammerickx and Smith (1978). Where crossed by
C22, the E.P.R. is characterized by a narrow (4
km) wide horst some 300 meters high.

the East Pacific Rise (Figure 1). The length of
the profile was about 90 kilometers, and extended
from the rise axis to a position about 57 kilome-
ters away (over crust from 0 to 0.7 Ma. in age).

A record section of the seismograms recorded
on the southwest profile is shown in Figure 2.
Easily visible in the section are crustal arri-
vals at ranges between 9 and 30 kilometers, man-
tle Pn between 30 and 62 kilometers and wide an-
gle reflections from the moho at ranges of 30 to
80 kilometers. No shear waves are visible in
these data.

The wide-angle moho reflections are striking
for they are clear and undelayed to within 3 ki-
lometers of the rise axis (measured normal to the
axis). The arrival becomes emergent near the
axis (range = 83 kilometers) and for two shots on
the other side of the rise (not shown) the signal
is totally lost. The decay in signal is not
surprising and suggests that the there may be
some low velocity or highly attenuating crustal
heterogeneity associated with the axis, perhaps a
magma chamber. However, the influence of this
hypothesized heterogeneity does not extend more
than 3 kilometers away from the axis; thus,
there is no evidence for an unusually large magma
chamber under this segment of rise. The large
source-receiver distances involved for these
shots, and the obliquity of the ray paths pres-
cribes caution in these conclusions, but if they
are true the small apparent size of the axial
magma chamber requires that the crust be consid-
erably cooler than conductive thermal models

would predict. This cooling is presumably the
result of hydrothermal circulation in the young
oceanic crust.

Large amplitudes can be observed at ranges of
25 to 32 kilometers (Figure 2). These are the
result of a triplication in the ray paths caused
by the moho transition zone. Large amplitudes
are also seen at ranges of 10 to 16 kilometers.
These suggest that a transition zone may also ex-
ist in the upper or middle crust.

We have attempted to duplicate the major fea-
tures of this record section using synthetic
seismograms. Some 60 models were tried, with the
best match and the resulting model shown in Fig-
ures 3 and 4 respectively. The synthetics repro-
duce most of the major features described above.
The only serious discrepancy is the misfit of
travel times at ranges 10 to 15 kilometers, which
probably were caused by lateral heterogeneities.
The major features of our model are an upper
crust with a steep gradient (2.98 km/s/km) over-
lying a zone of rather low velocity gradient (0.3
km/s/km). This in turn overlies a transition
zone between the upper and lower crust, which
brings about the increased amplitudes observed
between 10 and 15 kilometers.

The moho in our model has a thickness of 1.3
kilometers. If we define the bottom of the crust
as the point where the velocities exceed 7.5
km/s, we find a total crustal thickness of about
5 kilometers, much greater than those originally
derived for this profile from layered solutions
and similar to the "normal" oceanic crust des-
cribed in the introduction.

Northeast Profile

The profile extending northeast of the receiv-
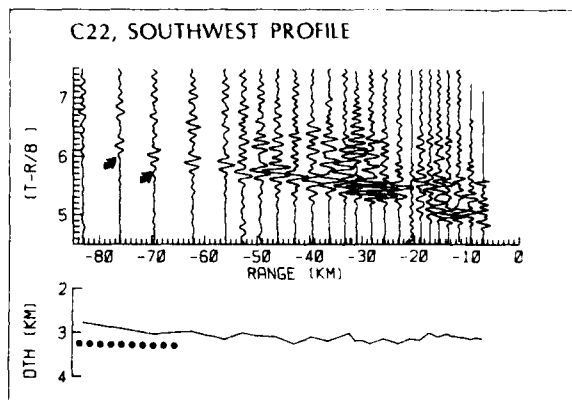ing ship was over seafloor which ranged from 57

Fig. 2. A record section of the southwest pro-
file. The location of the rise is at about 85 km.
Bathymetry is plotted beneath the profile, the
dotted region is that portion of the bathymetry
lying within 10 kilometers of the rise axis (when
measured normal to the rise axis). The arrows de-
note two examples of the wide-angle moho reflec-
tions noted in the text. All of the record sec-
tions shown in this paper have been plotted with a
reducing velocity of 8 km/s, their amplitudes have
been scaled for range and shot size, and the
travel times have been corrected for bathymetric
variations.

to over 90 kilometers away from the rise axis
(0.7 to 1.2 million year old crust). Like the
the southwest profile, the northeast line dis-
played an increase in amplitudes at ranges of
over 11 kilometers (Figure 5). However, at
ranges of 40 to 53 kilometers, the amplitudes for
most of the seismograms are huge. Although Pn is
not well developed in this profile, we suspect
that that these amplitudes are caused by the moho
triplication enhanced by the presence of bathyme-
tric variations beneath the shots. If so, the
moho triplication occurs at a greater range than
that of the southwest profile, suggesting that
the crust is thicker to the northeast.

We had greater difficulty in modeling the nor-
theast profile, and the best model and synthetics
are shown in Figures 4 and 5 respectively. We
were able to produce the increased amplitudes at
12 kilometers by introducing a transition zone in
the crust. It lies at a depth of about 1.7 ki-
lometers below the seafloor, and is slightly
deeper and more gradual than that of the
southwest profile. Above this transition zone
the velocities are higher than they are for the
southwest profile. The model includes a thin
(0.7 km) zone of relatively low velocity gradient
(0.4 km/s/km) the very top of the crust.

The total crustal thickness for the northeast
profile is about 7.0 km, two kilometers thicker
than that to the southwest. The moho itself is
thinner. This model does not provide the high
amplitude moho triplication we observe, but no
models were successful in this, again indicating
that bathymetry has influenced the amplitudes.

Fig. 4. The best fitting velocity depth models
for the southwest (solid) and northwest (dashed)
profiles. Arrows denote the upper crustal zone
("layer 2C"). "M" denotes the position of the
moho in each model.

Interpretation and Conclusions

In Figure 4 we display the two models which
best fit the data from our profiles. Both models
display high velocity gradients in the upper
crust, which typify normal oceanic crust. Menard
(1967) noted that "layer 2" seemed to be thinner
for crusts formed at ridges with higher spreading
rates. While it is difficult to directly compare
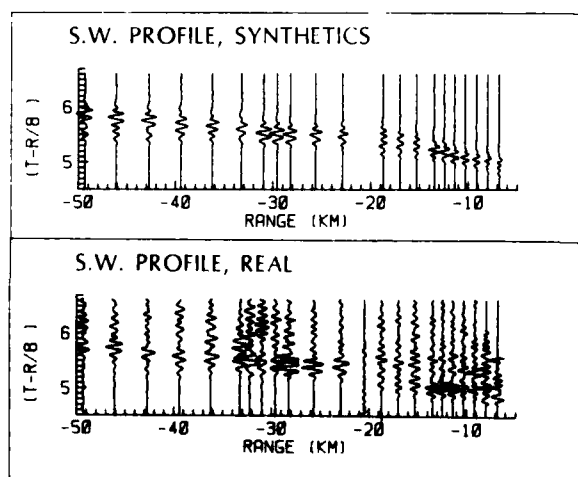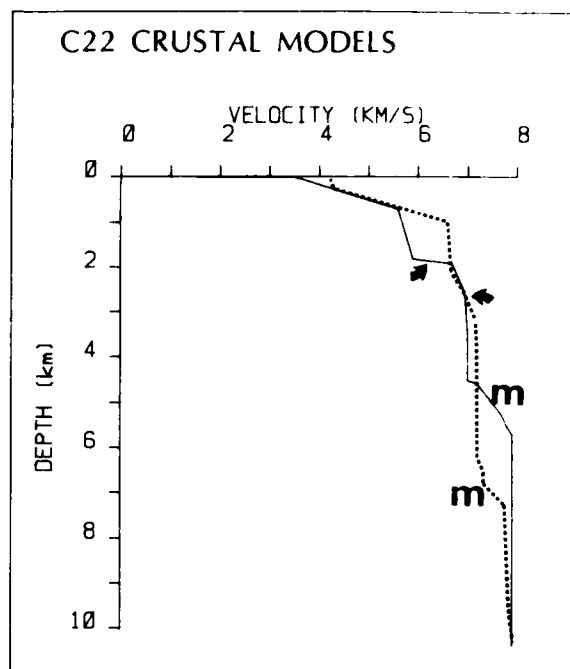our models with layered structures, our results

indicate that Menard's observed trend cannot be
extended to the very high spreading rates of
15°S.

Both profiles display a region of low velocity
gradient overlying a transition zone in the upper
part of the crust. For the southwest profile
these features are quite similar, in velocities
and depths, to those described for crust gener-
ated at slower spreading rates (Spudich et al.,
1978; Lewis and Garmany, 1982; Bratt and Purdy,
1984). Bratt and Purdy (1984) argued that the
transition zone marked a decrease in porosity as-
sociated with the change in lithology from pillow
basalts to sheeted dikes. We note, however, that
the reported depths of these transition zones are
invariably greater than 1 kilometer, while many
times the pillow basalt-sheeted dike boundary, as
noted for ophiolites (e.g. Christensen and
Salisbury, 1975) and oceanic cores (Anderson et
al., 1982) is less than 1 kilometer. We would
argue that this transition zone is more likely
explained as a change in porosity and/or mineral-
ization as originally suggested by Salisbury and
Christensen (1978). The depth of this boundary
depends upon hydrothermal circulation and the
temperature field in the crust and is not neces-
sarily tied to a particular lithologic change.

For the profile to the northeast, the region
of low gradient and the transition zone do not
occur until the crustal velocities have reached
"layer 3" values (Figure 4). This difference
could be consistent with the mechanism cited
above; the porosities above the transition zone
for the northeast profile are simply lower than

Fig. 3. Record sections for synthetics and the
corresponding real data for the southwest profile.

N.E. PROFILE, SYNTHETICS
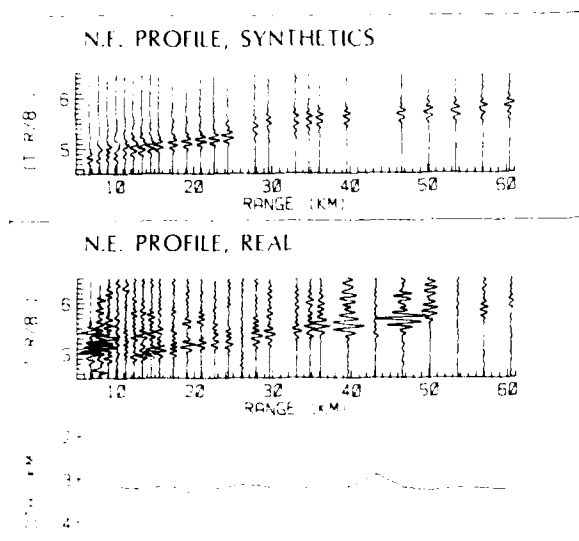

N.E. PROFILE, REAL

Fig. 5. Record sections for synthetics and the corresponding real data for the northeast profile. Notice the large amplitudes on the data which are not duplicated in the synthetics. These are partially attributed to the focussing of energy away from the small seamount (over which the amplitude is very small) seen on the bathymetry plot below.

they are under the southwest profile. The transition zone would still represent a decrease in the already low porosity and/or a change in minerals within the pores.

We are reluctant to attach much significance to the differences in crustal thickness between the two profiles. Certainly the older profile has a thicker crust which could have formed after the crust was spread away from the ridge. Equally likely is that this apparent thickening reflects the natural variability of the crust.

In conclusion, the similarities and differences between these two profiles are typical of the oceanic crust, and the features we observe indicate that this crust is "normal"; that is , we do not see any systematic variations we would associate with the high spreading rates of the adjacent ridge. The very thin crust originally derived for Capricorn 22 has not held up under our analysis, demonstrating the value of reanalysing these high quality data using modern techniques.

These data provide no evidence for an unusually large magma chamber under the fast spreading East Pacific Rise. This tentative result suggests that water penetration must cool the crust and prevent the formation of such exotic features. This conclusion is consistent with those made from experiments on other segments of the East Pacific Rise (see Macdonald, 1983 for a review) and argues that hydrothermal rather than conductive cooling is the dominant factor controlling the size of crustal magma chambers under the East Pacific Rise.

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